Perfluorinated Compounds in Human Breast Milk from Several Asian Countries, and in Infant Formula and Dairy Milk from the United States

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The occurrence of perfluorinated compounds (PFCs) in human blood is known to be widespread; nevertheless, the sources of exposure to humans, including infants, are not well understood. In this study, breast milk collected from seven countries in Asia was analyzed ($n = 184$) for nine PFCs, including perfluorooctanesulfonate (PFOS) and perfluorooctanoate (PFOA). In addition, five brands of infant formula ($n = 21$) and 11 brands of dairy milk ($n = 12$) collected from retail stores in the United States were analyzed, for comparison with PFC concentrations previously reported for breast milk from the U.S. PFOS was the predominant PFC detected in almost all Asian breast milk samples, followed by perfluorohexanesulfonate (PFHxS) and PFOA. Median concentrations of PFOS in breast milk from Asian countries varied significantly; the lowest concentration of 39.4 pg/mL was found in India, and the highest concentration of 196 pg/mL was found in Japan. The measured concentrations were similar to or less than the concentrations previously reported from Sweden, the United States, and Germany (median, 106–166 pg/mL). PFHxS was found in more than 70% of the samples analyzed from Japan, Malaysia, Philippines, and Vietnam, at mean concentrations ranging from 6.45 (Malaysia) to 15.8 (Philippines) pg/mL. PFOA was found frequently only in samples from Japan; the mean concentration for that country was 77.7 pg/mL. None of the PFCs were detected in the infant-formula or dairy-milk samples from the U.S. except a few samples that contained concentrations close to the limit of detection. The estimated average daily intake of PFOS by infants from seven Asian countries, via breastfeeding, was 11.8 ± 10.6 ng/kg bw/day; this value is 7–12 times higher than the estimated adult dietary intakes previously reported from Germany, Canada, and Spain. The average daily intake of PFOA by Japanese infants was 9.6 ± 4.9 ng/kg bw/day, a value 3–10 times greater than the estimated adult dietary intakes reported from Germany and Canada. The highest estimated daily intakes of PFOS and PFOA by infants from seven Asian countries studied were 1–2 orders of magnitude below the tolerable daily intake values recommended by the U.K. Food Standards Agency.

Introduction

Perfluorinated compounds (PFCs), including perfluorooctanesulfonate (PFOS), perfluorohexanesulfonate (PFHxS), perfluorooctanoate (PFOA), and perfluorononanoate (PFNA), have been found in human blood from the general populations, from developed and developing countries alike (*1–7*). Mean concentrations of PFOS and PFOA reported for American children aged 2–12 were 37.5 and 4.9 ng/mL, respectively; these concentrations were similar to the values reported for adults (*8, 9*). PFOS and PFOA have been found in cord blood samples from the United States, Germany, and Japan (*10–12*). Concentrations of PFOS and PFOA in cord blood were correlated with the concentrations in maternal blood, indicating transplacental transfer of PFCs and in utero exposures. PFCs were also reported to be present in the blood of one-day-old neonates from New York State (*13*). Lactational transfer of PFCs has been suggested as a source of PFC exposure for infants based on the analysis of breast milk from the U.S., Sweden, Germany, and China (*14–17*).

Gestational exposure of PFOS and PFOA in laboratory rodents has been shown to reduce gestational length, birth weight, and weight gain, and to reduce postnatal survival during early life stages (*18–23*). Lactational exposure reduced the body weight gain in pups nursed by PFOS- or PFOA-exposed dams (*24, 25*). However, health effects of PFCs in human infants at current exposure levels, which are 3 orders of magnitude lower than the concentrations used in laboratory animal exposure studies, are unknown. Concentrations of PFOS and PFOA in cord blood were negatively associated with birth weight, ponderal index, and head circumference (*26*). Maternal PFOA concentrations were negatively associated with birth weight, length, and abdominal/head circumferences in children from Denmark (*27, 28*). Although the three studies (*26–28*) suggested an association between gestational PFC exposure and birth outcomes, another study involving mothers occupationally exposed to PFOS did not find any association between maternal exposure and birth weight of the babies (*29*).

Dietary intake is a pathway for PFC exposure in adults. Diet was reported to contribute 61% of the estimated total daily intake of 410 ng/person/d for PFOS and perfluorocarboxylates in adults in Canada (*30*). Diet was shown to contribute 1.4 and 2.9 ng/kg bw/d for PFOS and PFOA intakes, respectively, in German adults (*31*). A study on dietary intake of PFCs in Spain showed that daily intake of PFOS by children aged 4–9 years (2.3 ng/kg bw/d) was twice as high as that estimated for adult males (1.07 ng/kg bw/d) (*32*).

Breast milk is strongly recommended for newborn babies because it provides balanced nutrients and immunoglobulins to enhance the immune system and to fight against infections (http://www.who.int/nutrition/publications/Planning_guide.

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pdf). Recent studies on PFC measurements in breast milk have focused on samples collected from North America and Europe (*14*–*17*); little is known about PFC concentrations in breast milk, or exposure levels in infants, in Asian countries. Infant formula or dairy milk is a supplemental diet given to newborn babies, and is given as the sole diet when the mother is unable to produce milk. Occurrence of PFCs in infant formula or dairy milk has not been determined.

In the present study, breast milk collected from seven Asian countries—Japan, India, Malaysia, Philippines, Indonesia, Vietnam, and Cambodia—was analyzed to determine concentrations of nine PFCs: perfluorobutanesulfonate (PFBS), PFHxS, PFOS, perfluoroheptanoate (PFHpA), PFOA, PFNA, perfluorodecanoate (PFDA), perfluoroundecanoate (PFUnDA), and perfluorododecanoate (PFDoDA). In addition, infant formula from five manufacturers representing the majority of the U.S. market and 11 brands of dairy milk purchased from retail stores in Washington, DC, and Albany, NY in 2007 and 2008 were analyzed. Daily intakes of PFCs by infants were estimated based on the ingestion rates of and PFC concentrations in breast milk (Asia), and in infant formula and dairy milk (United States).

Materials and Methods

Samples. A total of 184 human breast milk samples were obtained from nursing mothers from Japan ($n = 24$), India ($n = 39$), Malaysia ($n = 13$), Philippines ($n = 24$), Indonesia ($n = 20$), Vietnam ($n = 40$), and Cambodia ($n = 24$). Samples were primarily from women living in the major cities in each of the countries, and were collected during 1999 to 2005. Mothers' ages ranged from 17 to 40 years, with an average of 27 years. Samples from Japan were all from mothers who were nursing for the first time. Samples from other Asian countries included first-time nursing mothers and mothers who had nursed previous infants. Further details of the samples and sampling locations are given in the Supporting Information (Table S1). Samples were collected through the international collaboration of scientists in Asian countries and were archived at −20 °C at the Environmental Specimen Bank (ES-Bank) at Ehime University, Matsuyama, Japan. A small portion of each archived milk sample was analyzed for PFCs at the Wadsworth Center, New York State Department of Health.

In addition to the collection of breast milk samples, infant formula samples from five manufacturers representing >99% of the U.S. market ($n = 21$) were purchased from retail stores in Washington, DC and Boston, MA, in 2007. Most of the infant formula samples were milk- or soy-based, purchased as powders and ready to use or concentrated liquids, packaged in plastic, glass, cardboard, or metal containers. Both organic and non-organic formulations were included. Further details of the infant formula samples are given in the Supporting Information (Table S2). Eleven brands of dairy milk were purchased ($n = 12$) from retail stores and local farms in Albany, NY in 2008. Dairy milk samples were primarily homogenized cow milk, packaged in plastic or paper containers. Infant-formula and dairy-milk samples were kept at 4 °C and were opened just before analysis, prepared as recommended. For example, powdered formula samples were dissolved in water (Milli-Q water was used), and the concentrated liquid formula samples were diluted 1:1 with Milli-Q-water before analysis. Ready-to-feed liquid formulas and dairy milk were analyzed directly from the package.

Analysis. All of the samples were extracted with Oasis weak anion exchange cartridges (WAX; 6 cc, 150 mg; Waters, Milford, MA) following the solid-phase extraction (SPE) method described previously (*14*). Target compounds were identified and quantified by high-performance liquid chromatograph (HPLC, Agilent 1100 Series) coupled with an API 2000 electrospray triple quadrupole mass spectrometer (ESI-MS/MS, Applied Biosystems; Foster City, CA). Further details of the analysis are given in Supporting Information.

Quality Assurance and Quality Control. The analytical method was evaluated by spiking known amounts of PFCs into cow milk and human milk; the average recoveries of native and labeled PFCs ranged from 78 to 100% in both of the milk matrices (*14*). The recoveries of the four ^{13}C-labeled internal standards in this study, which were spiked into all samples prior to extraction, were 104 ± 17% (mean ± SD) for $^{13}C_4$–PFOS, 139 ± 34% for $^{13}C_4$–PFOA, 113 ± 27% for $^{13}C_2$–PFNA, and 124 ± 44% for $^{13}C_2$–PFDA in breast milk samples and in infant formula and dairy milk samples they were 84 ± 10% for $^{13}C_4$–PFOS, 138 ± 37% for $^{13}C_4$–PFOA, 129 ± 77% for $^{13}C_2$–PFNA, and 116 ± 69% for $^{13}C_2$–PFDA. Matrix spikes were prepared by spiking known amounts of 9 native PFC standards (1 ng of each) into 5 randomly selected breast milk samples and passed through the entire analytical procedure. The matrix spike recoveries for PFOS, PFOA, and PFHxS were 77 ± 6%, 106 ± 15%, and 91 ± 18%, respectively. The average matrix-spike recoveries for the other six PFCs ranged from 70% for PFUnDA to 94% for PFDA. Method blanks ($n = 6$) and field blanks ($n = 2$) contained trace levels of a few of the PFCs, at concentrations ranging from 0.5 ± 0.5 pg/mL for PFBS to 21.2 ± 5.4 pg/mL for PFOA. The limit of quantitation (LOQ) was determined to be three times the average concentration found in the blanks.

Data Analysis. Quantification was performed using a $1/x$ weighted eight-point calibration curve prepared by means of external standards in methanol. Concentrations in milk and infant formula were subtracted from the average blank values. Reported concentrations for PFOS, PFOA, PFNA, and PFDA were corrected by respective individual internal standard recoveries, while the concentrations for other PFCs were not corrected for the recoveries of internal standards. Concentrations below the LOQ were assigned $^1/_2$ the value of the LOQ for statistical analysis. Mean and median values were calculated only if more than 70% of the samples had concentrations above the LOQ. Because the data were not normally distributed, nonparametric statistical tests were applied to assess the statistical significance. The Mann–Whitney U test was used to compare differences in PFC concentrations among the Asian countries. Spearman's correlation analysis was used to examine the relationship between mother's age and PFC concentrations. Statistical significance was set at the level of $p \leq 0.05$.

Results and Discussion

PFC Concentrations in Breast Milk, Infant Formula, and Dairy Milk. Concentrations of PFCs in breast milk samples collected from the three cities in India did not differ significantly from one another and therefore were treated as one group. Samples from the Philippines, collected in 2000 and in 2004, were also grouped together, since no temporal difference in PFC concentrations was found between the two sampling periods. PFOS was the predominant compound found in the Asian human breast milk samples; PFOS was detected in 85% of the samples from India and in 100% of the samples from the other sampling countries (Table 1). The mean concentration of PFOS in breast milk ranged from 46.1 pg/mL in samples from India to 232 pg/mL in samples from Japan. PFHxS was the second predominant PFC, detected overall in more than 50% of the breast milk samples. PFOA was found in 96% of the samples from Japan at a mean concentration of 77.7 pg/mL. PFBS, PFHpA, and PFNA were found in very few of the samples analyzed. Other long-chain perfluorinated carboxylates such as PFDA, PFUnDA, and PFDoDA were not detected in any sample at concentrations above the LOQ.

PFC concentrations in infant formula from the United States were 10-fold lower than the concentrations found in the Asian breast milk samples. PFOS (LOQ = 11.0 pg/mL) was detected in one formula sample at a concentration of 11.3 pg/mL. PFHxS (LOQ = 1.35 pg/mL) was detected in two formula samples at concentrations of 1.36 and 3.59 pg/mL. Other PFCs were not

TABLE 1. Summary of PFCs Concentrations (pg/mL) in Breast Milk Samples from Seven Asian Countries and in Infant-Formula and Dairy-Milk Samples from the United States[a]

	PFOS	PFOA	PFHxS	PFNA	PFBS	PFHpA
Breast milk						
Japan (Ehime; 1999), $n = 24$						
range	140–523	<42.5–170	<1.66–18.2	<8.82–23.9	<1.11	<4.45–13.9
positive (%)	100	92	92	13	0	25
mean (median)	232 (196)	77.7 (67.3)	7.55 (6.45)			
Malaysia (Penang; 2003), $n = 13$						
range	48.7–350	<42.5–90.4	<1.66–13.3	<8.82–14.9	<1.11–16.5	<4.45
positive (%)	100	23	85	8	8	0
mean (median)	121 (111)		6.45 (6.68)			
Philippines (Quezon; 2000 and 2004), $n = 24$						
range	27.0–208	<42.5–183	<1.66–58.9	<8.82–25.0	<1.11–17.4	<4.45–34.8
positive (%)	100	29	92	17	13	8
mean (median)	97.7 (104)		15.8 (13.3)			
Indonesia (Jakarta, Purwakarta; 2001), $n = 20$						
range	25.4–256	<42.5	<1.66–6.23	<8.82–135	<1.11	<4.45–7.32
positive (%)	100	0	45	5	0	5
mean (median)	83.6 (67.2)					
Vietnam (Hanoi, Ho Chi Minh; 2000 and 2001), $n = 40$						
range	16.9–393	<42.5–89.2	<1.66–26.8	<8.82–10.9	<1.11–3.98	<4.45–6.88
positive (%)	100	3	73	5	10	18
mean (median)	75.8 (58.5)		6.81 (4.33)			
Cambodia (Phnom Penh; 2000), $n = 24$						
range	17.2–327	<42.5–132	<1.66–18.6	<8.82–12.3	<1.11–4.86	<4.45–38.4
positive (%)	100	4	13	13	8	29
mean (median)	67.3 (39.9)					
India (Chidambaram, Kolkata, Chennai; 2002, 2004, and 2005), $n = 39$						
range	<11.0–120	<42.5–335	<1.66–13.3	<8.82	<1.11–8.86	<4.45
positive (%)	85	8	36	0	5	0
mean (median)	46.1 (39.4)					
Infant formula						
United States (Washington, DC; 2007), $n = 21$						
range	<11.0–11.3	<48.3	<1.35–3.59	<2.20	<0.7	<1.2
positive (%)	5	0	10	0	0	0
Dairy milk						
United States (Albany, NY; 2008), $n = 12$						
range	<11.0	<48.3	<1.35–3.82	<2.20	<0.7	<1.2
positive (%)	0	0	8	0	0	0

[a] Mean and median values were calculated when more than 70% samples were positively detected in concentrations above the quantitation limit (LOQ). PFDA, PFUnDA, and PFDoDA were not found in any of the samples analyzed at concentrations above the LOQs (17.8, 24.0, and 12.7 pg/mL).

detected in any of the formula samples analyzed. Concentrations of PFCs in dairy-milk samples were similar to values found for the infant formula samples. None of the PFCs was detected in any of the dairy milk samples. PFHxS was found in one soy-milk sample, at a concentration of 3.82 pg/mL.

Geographical Distribution. Among the seven Asian countries studied, the highest concentrations of PFOS and PFOA were found in breast milk samples from Japan. Concentrations of PFOS and PFOA were significantly higher in breast milk collected from Japan than from the other Asian countries ($p < 0.05$) (Figure 1; Table 1). Concentrations of PFOS in breast milk collected from Malaysia, Philippines, and Indonesia were significantly higher than the concentrations in samples from Vietnam, Cambodia, and India. The lowest concentration of PFOS was found in breast milk from India. The concentrations of PFHxS were significantly higher in milk from the Philippines than in milk from Japan, Vietnam, and Malaysia (Figure 2); for the remaining three countries, PFHxS was infrequently detected.

PFOS and other PFCs have been reported in breast milk from China, Sweden, Germany, Hungary, and the United States (*14–17*). PFOS concentrations in breast milk from Asian countries, in the present study, were within an order of magnitude of the concentrations reported for the United States and Europe (Figure S1). The median concentration of PFOS reported in breast milk was higher in Hungary (330 pg/mL) than in the other countries studied so far (*16*). Concentrations of PFOS in breast milk from Japan, in the present study, were similar to the concentrations reported in Sweden (median: 166 pg/mL) (*14*). Concentrations of PFOS in breast milk from Malaysia and the Philippines were similar to the concentrations reported for the United States (median: 106 pg/mL) (*13*), Germany (median: 123 pg/mL) (*16*), and China (median: 100 pg/mL) (*15*). Concentrations of PFCs in breast milk from Vietnam, Cambodia, and India were 40–50% lower than the concentrations reported for the United States, Germany, and China.

The geographical pattern of PFOS distribution in breast milk from Asian countries resembled the pattern reported for PFOS in blood from those countries (*3*). For example, concentrations of PFOS were reported to be the lowest in human blood from India (*3*), a pattern similar to that in breast milk, in this study. Mean serum concentrations of PFOS in female donors from

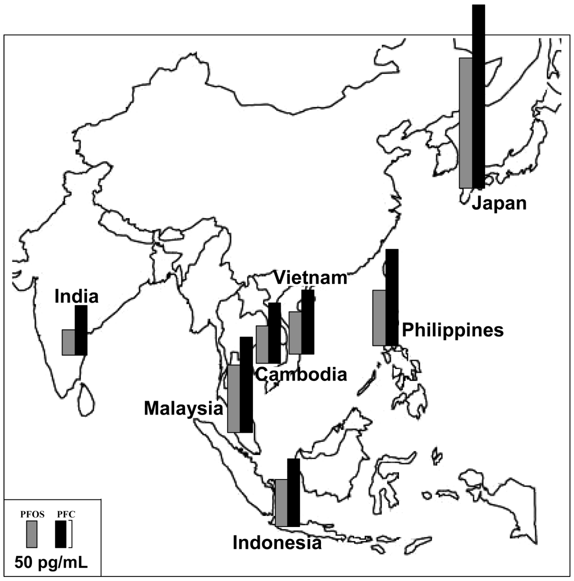

FIGURE 1. Mean concentration (pg/mL) of PFOS (gray bars) and total PFC (sum of PFOS, PFOA, PFHxS, PFNA, PFBS, and PFHpA) (black bars) in breast milk samples ($n = 184$) from seven Asian countries.

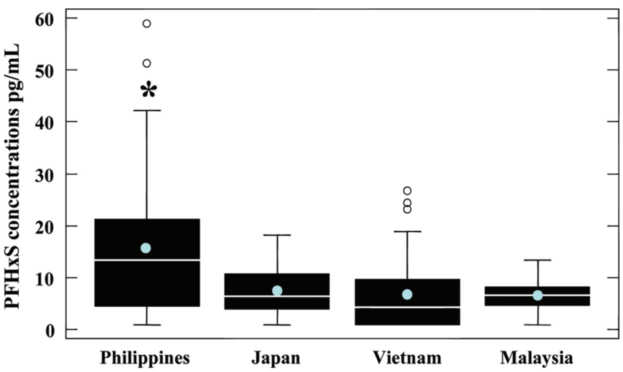

FIGURE 2. Concentration of PFHxS (pg/mL) in breast milk from the Philippines ($n = 24$), Japan ($n = 24$), Vietnam ($n = 40$), and Malaysia ($n = 13$). Asterisk indicates a statistically significant ($p \leq 0.05$) higher concentration in the Philippines than in the other three countries.

Japan, Malaysia, and India were 20, 12, and 2.3 ng/mL, respectively (*3*); a similar trend was found in breast milk, with PFOS concentrations of 232, 121, and 46.1 pg/mL for Japan, Malaysia, and India, respectively (Figure S2).

High concentrations of PFCs in breast milk from Japan can be related to the production and usage of a number of consumer products that contain PFCs (*33*). Nevertheless, since 2001, reductions in PFOS concentrations in human blood, as well as in biota from the United States have been reported (*34, 35*), due to the phase out in the production of PFOS-based compounds by 3M Company, the leading manufacturer. The breast milk samples from Japan were collected in 1999, a few years earlier than the samples collected from other countries. There is no information available on the production of PFCs in Asian countries other than Japan and China. It is worth noting that the concentrations of PFOS in breast milk from countries with high gross domestic product (GDP) (e.g., United States, Sweden, Hungary, Germany, and Japan) (*36*) were higher than those in countries with low GDP (e.g., Vietnam, Indonesia, India, and Cambodia). In addition to economic conditions, sociological and cultural factors, as well as individual consumer habits, can contribute to the geographical variability in exposure levels of PFCs.

The breast milk samples analyzed in this study had been previously analyzed for persistent organic pollutants such as polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) (*37, 38*). Concentrations of PBDEs in breast milk from Japan, Malaysia, and the Philippines were greater than the concentrations reported for Cambodia, Vietnam, and India (*37*). That finding is similar to what we have found for PFOS, suggesting some similarities in human exposures to PFOS and PBDEs exist in these Asian countries (Figure S2). PFOS has been used as a surface protectant in many consumer products such as textiles, leathers, and food packaging, to repel oil, dust, and grease (*33*). PBDEs have been used as flame retardants in various consumer products such as textiles, plastics, and electronic equipment, to impart resistance to flammability (*37*). It is believed that consumer products treated with PFCs and/or PBDEs are potential sources of exposure to PFOS and PBDEs in the general population.

Nursing History and PFC Concentrations. Breast milk samples analyzed in this study, except for those from Japan, were collected from mothers who had nursed previously as well as those who were nursing for the first time. Previous nursing can potentially reduce the concentrations of PFOA in breast milk (*14*). However, in this study, the concentrations of PFOS and PFHxS in the milk of mothers who were nursing for the first time were not statistically different from those of mothers who had nursed previously. Nevertheless, median PFOS concentrations in the milk of Malaysian and Cambodian mothers, who were nursing for the first time were 27−100% higher than concentrations in the milk of mothers who had previously nursed, from the same countries (Table S3). However, confidence in this interpretation is tempered by uncertainties in the grouping of samples based on the number of previous children.

Correlations among PFCs. Concentrations of PFOS, PFOA, and PFHxS in breast milk from Japan were significantly correlated with each other (Spearman's coefficient, $p < 0.01$). PFOS and PFHxS were significantly correlated (Spearman's, $p < 0.05$) in breast milk from the Philippines, Vietnam, and Malaysia. Correlations between PFOS and PFHxS, as well as between PFOS and PFOA, in breast milk from Japan suggest coexposure to several PFCs.

Concentrations of PFOS, PFOA, and PFHxS were not correlated with mother's age when samples were analyzed individually for each of the countries. Nevertheless, when all of the samples were considered together, concentrations of PFOS in breast milk were significantly positively correlated (Spearman's, $p < 0.001$, Figure S3) with the age of the mother. This comparison ($n = 72$) suggests increase in PFOS burden with age.

Daily Intake of PFCs via Breast Milk, Infant Formula, and Dairy Milk. The mean consumption level of breast milk by infants between ages of 1 and 6 months is 742 mL/day, according to the United States Environmental Protection Agency (EPA) (*39*); this consumption rate is consistent with the rates reported in several other countries (*39, 40*). Using this value, we estimated the average daily intake (ADI) of PFOS via breastfeeding by infants with an average body weight (bw) of 6 kg to be 11.8 ± 10.6 ng/kg bw/day, for the seven Asian countries studied; this intake value varied from 5.7 ± 4.4 ng/kg bw/day for Indian infants to 28.7 ± 11.7 ng/kg bw/day for Japanese infants (Table 2). The ADI of PFOA was 9.6 ± 4.9 ng/kg bw/day for Japanese infants. The ADI of total PFCs (sum of PFOS, PFOA, PFHxS, PFBS, PFHpA, and PFNA) was 18.2 ± 14.3 ng/kg bw/day, over all of the seven Asian counties studied. Based on the highest concentrations measured, the highest ADIs for PFOS, PFOA, and total PFC were estimated to be 64.6, 41.3, and 88.7 ng/kg bw/day, respectively. Based on the concentrations of PFCs determined in infant formula and dairy milk from the United States, the maximum ADI of PFOS by infants was estimated to be ≤1.4 ng/kg bw/day; this value is an order of

TABLE 2. Estimated Daily Intakes (ng/kg bw/d) of PFOS and Total PFCs by Infants via Breastfeeding in Asian Countries, and via Infant Formula or Dairy Milk in the United States[a]

	PFOS		SUM1[b]		SUM2[c]	
via breast milk	mean	SD	mean	SD	mean	SD
Japan	28.7	11.7	39.2	16.3	40.5	16.7
Malaysia	15.0	9.3	19.7	12.0	20.9	12.3
Philippines	12.1	5.9	19.8	10.7	21.2	11.4
Indonesia	10.3	7.0	13.2	7.0	14.9	10.0
Vietnam	9.4	8.7	13.1	9.3	14.1	9.3
Cambodia	8.3	9.4	11.7	10.1	13.1	10.4
India	5.7	4.4	10.1	7.9	11.0	8.1
average	11.8	10.6	17.0	13.8	18.2	14.3
	max[d]		max		max	
via infant formula - U.S.	1.4		4.8		5.1	
via dairy milk - U.S.	0.7		4.1		4.4	

[a] Calculation is based on an average milk intake rate of 742 mL/day and an average body weight of 6 kg. [b] Sum of PFOS, PFOA, and PFHxS. [c] Sum of PFOS, PFOA, PFHxS, PFBS, PFHpA, and PFNA. [d] One-half the LOQ value was used for calculation when maximum concentration was below the LOQ.

magnitude lower than the ADI previously reported from breast milk consumption in the United States (*14*).

The calculated exposures to PFOS and other PFCs via breastfeeding were at least an order of magnitude higher than the exposures via formula feeding. Although formula feeding can reduce PFC exposures, breastfeeding provides unique nutrients and antibodies to strengthen infants' immune systems. As long as the intake of an environmental contaminant/toxicant via breastfeeding does not exceed the reference doses suggested by national/international health organizations, breastfeeding is still recommended by several agencies and advisory groups. Currently, there is no consensus reference dose established for the intake of PFOS and PFOA. The U.K. Food Standards Agency, Committee on Toxicology recommended tolerable daily intake (TDI) values of 300 and 3000 ng/kg bw/day for PFOS and PFOA, respectively, based on a thorough review of the findings of currently available toxicity studies (*41, 42*). The German Federal Institute for Risk Assessment determined a TDI of 100 ng/kg bw/day for PFOS by applying an uncertainty factor of 1000 to a NOAEL value from a two-generation reproductive toxicity study in rats (*43*). The Environmental Working Group (EWG) in the United States estimated a reference dose (RfD) of 25 ng/kg bw/day for PFOS, based on increase in mammary fibroadenomas in a chronic toxicity study in rats (*44*). The estimated ADI of PFOS in Asian infants in our study did not, in general, exceed the TDIs recommended by the U.K. and Germany, but it did exceed the RfD of EWG for certain individual samples.

The estimated ADI of PFOS by infants from the seven Asian countries via breastfeeding was 7−12 times higher than the adult dietary intakes values previously reported; the average dietary intake of PFOS by Canadian adults (>12 years old), Germans (17−45 years old), and Spanish adults (>10 years old) were estimated to be 1.6, 1.4, and 1.07 ng/kg bw/d, respectively (*30*−*32*). Our ADI values of PFOS for Asian infants were 4−6 times higher than the average dietary intakes estimated for Spanish children (aged 4−9 years) (*32*). ADIs of PFOA by Japanese infants were 3−10 times higher than the dietary intakes estimated for Canadian and German adults (1.0 and 2.9 ng/kg bw/d) (*30, 31*).

In summary, PFOS, PFHxS, and PFOA were found in breast milk samples collected from seven Asian countries, suggesting the prevalence of PFC exposure in populations in both developing and developed countries. Concentrations of PFOS in breast milk samples from Vietnam, Cambodia, and India were approximately 3−5 fold lower than the concentrations found in breast milk from Japan. Concentrations of PFCs in infant-formula and dairy-milk samples from the United States were approximately an order of magnitude lower than the concentrations in breast milk. The daily intake of PFOS by Asian infants via breastfeeding was 7−12 times higher than the dietary intakes previously reported for adult populations in Canada, Germany, and Spain. Further studies are needed to assess the effects of PFCs in early life stages.

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Supporting Information Available

Details of analytical methods and tables showing breast milk and infant formula samples, concentrations of PFOS and PFHxS in relation to parity, geographical comparison of serum and breast milk PFOS and PBDE concentrations, association between age and PFOS concentrations, and median concentration of PFOS (pg/mL) in breast milk from seven Asian countries (black bar; this study) compared with the concentrations reported for the U.S., China, Germany, Sweden, and Hungary. This material is available free of charge via the Internet at http://pubs.acs.org.

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